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(6) EXPERIMENTS USING A THREE-COMPONENT LASER-ANEMOMETRY SYSTEM ON A SUBSONIC FLOW WITH VORTICITY.

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EXPERIMENTS USING A THREE-COMPONENT LASER-ANEMOMETRY SYSTEM ON A SUBSONIC FLOW WITH VORTICITY

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SUMMARY

Experiments with a three-component laser anemometer on the wake and vortex structure behind a model wing at incidence in a 4ft × 3ft subsonic test section are described. Three colours from the output spectrum of an argon-ion laser were used for the three Doppler-difference arrangements. The complete optical system operated in backscatter and was mounted on a single table which could be translated in three orthogonal directions.

An integrated data acquisition and reduction system was used incorporating a photon correlator and a Honeywell 6/36 minicomputer. The output data consisted of mean-velocity and turbulence-intensity values for all three components at each measurement point. From these data, the mean-velocity components in the directions of the conventional tunnel axes could be derived by means of a linear transformation. However, the measured turbulence intensities do not yield the turbulence intensities for these components without additional assumptions or supplementary information.

Departmental Reference: IT 168

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1 INTRODUCTION

Previously reported experimental work in laser anemometry at Farnborough has been concerned exclusively with axisymmetric or two-dimensional flows at subsonic[1] and supersonic[2] speeds. However, in fluid dynamics, such flows are the exception, not the rule, and to gain experience of more general conditions studies were carried out of the wake and vortex behind a model wing installed in the test section of the 4 ft x 3 ft low-turbulence wind tunnel at Farnborough. This provided a well structured flow on which to develop a three component Doppler-difference system. It was also intended that the measurements with this non-intrusive equipment would provide an independent means of assessing and interpreting results obtained previously in the same flow with a five-tube yawmeter probe[3].

2 THE FLOW

Fig 1 shows the general form of the flow under study. Air curls out and over at the ends of the wing causing the flow to roll up into a vortex sheet. All the measurements were carried out in one vertical plane 3¾ chords downstream of the trailing edge. In this plane two vertical traverses through the wake and one horizontal traverse through the vortex were made. Also shown in Fig 1 are the directions of the three components of particular aerodynamic interest; u_A is the free-stream component parallel to the centre line of the tunnel, v_A is the cross-tunnel component and w_A is in the vertical direction.

3 APPARATUS AND EXPERIMENTAL PROCEDURE

The model wing (span 600 mm, chord 100 mm) was suspended upside down in the wind tunnel by wires which passed through holes in the ceiling to a balance mounted above the working section. The wing was set at an angle of 5^o to the flow. A window was fitted in the roof of the tunnel to allow laser light for the third axis to be introduced into the test section.

Fig 2 shows the optical layout of the three component Doppler-difference equipment. The various spectral lines in the output of an argon-ion laser were separated by a pair of Amici prisms. M_3, M_4 and M_5 are plane mirrors. The pairs of beams at wavelengths of 476.5 nm and 514.5 nm, produced by the beam-splitters BS_1 and BS_2, were arranged to intersect at a common point in the flow. A light framework was constructed to support mirrors and a beamsplitter for the third laser line at 488 nm; the output beams were transmitted vertically through the window in the roof of the tunnel and adjusted to intersect at the common

measurement point. A simple lens was placed before each beamsplitter to reduce the diameter at the intersection to about 1 mm.

Successful Doppler-difference anemometry experiments depend critically on the accurate determination and stability of the intersection angle of a pair of beams. For the experiments described here, the appropriate angles were determined by measuring the separation of the beams in each pair on a screen some 2 m from the crossover point. During the course of the work it became clear that the fringe size was changing slowly on some occasions. It is conjectured that the large temperature changes observed during the working day were causing the optical components to move relative to one another; it should be noted that the present design of beamsplitting prism, while of simple construction and convenient in use, amplifies the effect of any beam wander.

Three separate FW130 photon-counting photomultiplier tubes, each with the appropriate narrow-band filter in front of it were used to detect the scattered light. In the case of the two horizontal beam pairs the crossover region was imaged by 152 mm f/2 lenses onto 100 μm pinholes fitted to the tube housings. The detectors were aligned at angles of about 30° to the input beams and the overall magnification of each collecting system was about 0.2, so that the diameter of the field of view was 0.5 mm. Hence the axial extent of the observed scattering region was some 2 mm. In the case of the vertical (488 nm) beam, a 178 mm f/2.5 lens imaged the crossover onto a 200 μm pinhole. The detector for this component was aligned almost at right angles to the input beams. However the magnification of this collecting system was also about 0.2, so that the extent of the observed scattering region was approximately 1 mm in both length and diameter. All the transmitting and receiving optical components were mounted on a table which could be traversed in the three orthogonal directions coinciding with the conventional tunnel axes. Fig 3 is a view from the far side of the tunnel of the wing in the test section and part of the optical system.

When correctly aligned, the three collecting systems defined a probe volume of about 1.5 mm^3. However, during horizontal traverses near the core of the vortex, it became evident from both the output of the data-processing system and the signal count-rates that the axes of the collecting systems were not aligned on a common point. Although better alignment was obtained by introducing a fixed scatterer into the crossover region, inserting neutral density filters in front of the collecting lenses and maximising the count-rates, subsequent analysis revealed that, for some traverses, misalignment remained. Lack of experimental time precluded further improvements. 180

The flow was lightly seeded with sub-micron oil droplets from a commercial oil mist generator. The scattering characteristics of oil particles generated in this way have been the subject of a laboratory study[4]. The point of injection into the tunnel, well upstream of the settling chamber, was positioned for maximum effect by observing the light scattered from the laser beams in the test section. When traverses through the vortex were being carried out, the absence of scattered light from a region some 10 mm in diameter around the vortex core was a noticeable phenomenon. This effect must be due to the inability of all but the smallest oil droplets to follow faithfully a highly accelerating flow.

It was known before the experiment began that in certain places in the flow, such as the centre of the vortex, there is a change in sign of the velocities in the vertical and cross-tunnel directions. A simple Doppler-difference anemometer is insensitive to the sign of the flow and in order to remove the ambiguity where flow reversals may be occurring, a frequency-shifting device is normally used in one or both beams[1,5]. However to avoid the complications associated with frequency-shifting techniques, a set of orientations for the fringe systems was chosen which ensured that flow reversals never occurred. The directions selected were inclined at 45^{o} to the centre line of the tunnel, two in the vertical plane and the third in the horizontal plane, and the beam-pairs oriented accordingly.

The output of each photomultiplier tube was connected in turn to a Malvern Instruments 48-channel digital correlator, which was interfaced to a Honeywell 6/36 minicomputer for on-line data-processing.

4 DATA ACQUISITION AND ANALYSIS

It was found that correlation functions could occasionally be obtained in 25 ms which yielded velocity estimates agreeing to better than 1% with those obtained using much longer acquisition times. However, in general, it was found that integration times of 30 s or more were necessary to obtain autocorrelation data of satisfactory quality. Near the vortex core, where there was very little seeding, data acquisition generally occupied several minutes. At a few points in this region interpretation of the autocorrelation data was not possible.

The data from the correlator were processed with the aid of the Fourier transformation techniques described in detail elsewhere[6,7].

Velocity components in the directions of the normals to the three fringe systems, which we shall term the laser components and distinguish by the suffix

L , can be transformed to velocity components in the wind tunnel coordinates, which we shall term the aerodynamic components and distinguish by the suffix A , by the following equations:

$$u_A = \frac{1}{\sqrt{2}} (u_L + w_L)$$

$$v_A = -\frac{1}{\sqrt{2}} (u_L + w_L) + \sqrt{2} v_L$$

$$w_A = -\frac{1}{\sqrt{2}} (u_L - w_L) \quad ,$$

where u_L and w_L are the components in the vertical plane and v_L is the component in the horizontal plane. Mean values of the velocity components will be denoted by the appropriate capital letters and turbulence intensities by the symbol η with the appropriate suffix. The velocity components in the aerodynamic coordinate system are shown in Fig 1.

We note here that although the set of equations above holds equally well for the mean and fluctuating parts of the velocities, the data-processing method yields estimates for the mean and rms values of the individual velocity components in the laser coordinate system, and it can easily be shown that to derive values of the rms fluctuations (and hence turbulence intensities) in the aerodynamic components, a knowledge of other cross-correlation terms would be required.

All data-reduction systems used for analysing the autocorrelation functions obtained from Doppler-difference arrangements rest implicitly or explicitly on the supposition that the detector sees the whole of each particle transit through the sample volume, which is assumed to be essentially a slender cylinder[8]. In this experiment these conditions were violated, since the diameter and axial extent of the sample volume were similar, and the optical geometry was such that a significant part of every particle transit would have been obscured from the detector. However, the beam diameter was here very much greater than the fringe size, so that the autocorrelation function would not have been greatly affected over its observed length. Mention should also be made, in the case of the vortex traverses, of the large velocity gradients near the core. Except for a few special geometrical arrangements, analysis of their quantitative effects is complicated, even if the gradients are assumed to be linear, and for this experiment the standard data-analysis procedure, based on the assumption that the fluid velocity is constant at any given instant throughout the measuring volume, was used.

We conclude therefore that mean values for the velocity components are probably accurate, but that the estimates of turbulence intensity near the vortex core do not indicate real values. On the other hand, turbulence measurements obtained in the wake, where velocity gradient problems were largely absent, should be more truly representative.

Meaningful estimates of the turbulence intensity with the desired resolution could have been achieved by using beams of 200 μm together with much smaller fringes, although severe problems of mechanical stability and in the optical arrangement would have been encountered.

5 RESULTS

The results of a vertical traverse through the wake near the centre-line are displayed in Figs 4 to 6. Fig 4 shows the laser-component velocities as a function of height. The data as originally plotted showed the minimum of one curve (U_L) to be slightly displaced from the other two. (The cause of this misalignment has been discussed in section 3.) The minima of the curves should coincide to within the accuracy of the measurements[3], since streamwise flow predominated and the three components were all at 45^o to the tunnel axis. It was necessary to displace the curve for U_L 1 mm in order to achieve alignment. Fig 5 shows the apparent turbulence intensities for the laser components. It can be seen that the turbulence increases in the region of the wake, as is to be expected.

The aerodynamic components of mean velocity derived from Fig 4 are shown in Fig 6. The velocity component along the tunnel axis U_A takes mainly the free-stream value except for a small dip in the wake. The small negative value of the vertical component W_A manifests the 'downwash' behind the wing.

Another traverse through the wake, but closer to the wing tip, showed broadly similar features. The major difference in the results of Fig 7 is that the cross-tunnel velocity component V_A has a steeper gradient through the wake, indicating a higher degree of vorticity there, (note the change of scale for V_A in Figs 6 and 7).

Figs 8 to 10 were obtained from a horizontal traverse through the vortex, carried out, because of practical limitations, in two stages on consecutive days. Both stages included the vortex core. In combining the data to form the complete set, account had to be taken of the misalignment problems referred to in section 3; because of these, the location of the partial traverses relative to one another was not known precisely. However, plots of the experimental data, which

consisted of the mean velocity, turbulence intensity and signal level (count rate) for the three components at each measurement point, revealed pronounced features in the region of the vortex core, with the aid of which a probable common origin could be established. The resulting combined graphs of mean velocity are shown in Fig 8. At the point of closest approach to the centre of the vortex it was found impossible through lack of signal to obtain an estimate for the value of W_L and the associated turbulence intensity. The absence of this data point is indicated by the dotted lines in Figs 8 to 10.

The associated apparent turbulence intensities are shown in Fig 9. It can be seen from Fig 8 that there were relatively steep velocity gradients near the centre of the vortex and these, combined with the finite extent of the measuring volume, result in an over-estimate for the computed turbulence levels. It is thought that the peaks in these curves in the region of the vortex are largely due to this effect.

Fig 10 shows the derived aerodynamic components. The velocity component along the tunnel axis, U_A , shows a 20% drop from the free-stream value of 32 m/s in the vicinity of the vortex centre, while the cross-tunnel component V_A , which starts at 1 m/s becomes negative and attains a value of about -4 m/s near the centre of the vortex. It then returns to its original value. The most likely explanation for this behaviour is that the traverse passed slightly above the centre of the vortex. The shape of the curve for the vertical velocity component W_A is consistent with the expected behaviour of a rotating flow in that the direction of the velocity changes at the centre of the vortex and the first derivative of the curve is symmetric about this point.

6 CONCLUSIONS

This paper has described an experimental system designed to measure the three-dimensional flow behind a model wing at incidence. Some results obtained with it have also been presented. It has been demonstrated that the simple addition of a third Doppler-difference arm to an existing proven two-component arrangement generates a number of new problems. The most severe of these was the precise alignment of three independent detector systems, essential if a common probe volume was to be achieved. A considerable simplification would result from the use of a single detector system with a set of interchangeable filters. Alternatively, a common laser line could be used and the appropriate beam-pairs selected successively, either with a mechanical shutter or with an active optical device such as a Bragg cell. These methods would generally result

in no loss of experimental efficiency since, for economic reasons alone, it is unlikely that more than one set of correlator and minicomputer equipment would be available.

The other major problem was the temporal variation of fringe size; it should be noted that minute changes of beam direction will be amplified by the simple beam-splitters employed. Two solutions to this problem being actively pursued are the design of a compensating beam-splitter and the development of an accurate fringe measuring device.

Comparative studies of the results reported here with those obtained in the same regions of the flow using the five-tube yawmeter probe are in progress.

Acknowledgments

Thanks are due to E.C. Maskell and P.B. Earnshaw of Aerodynamics Department for valuable discussions on the fluid mechanical aspects of the experimental programme.

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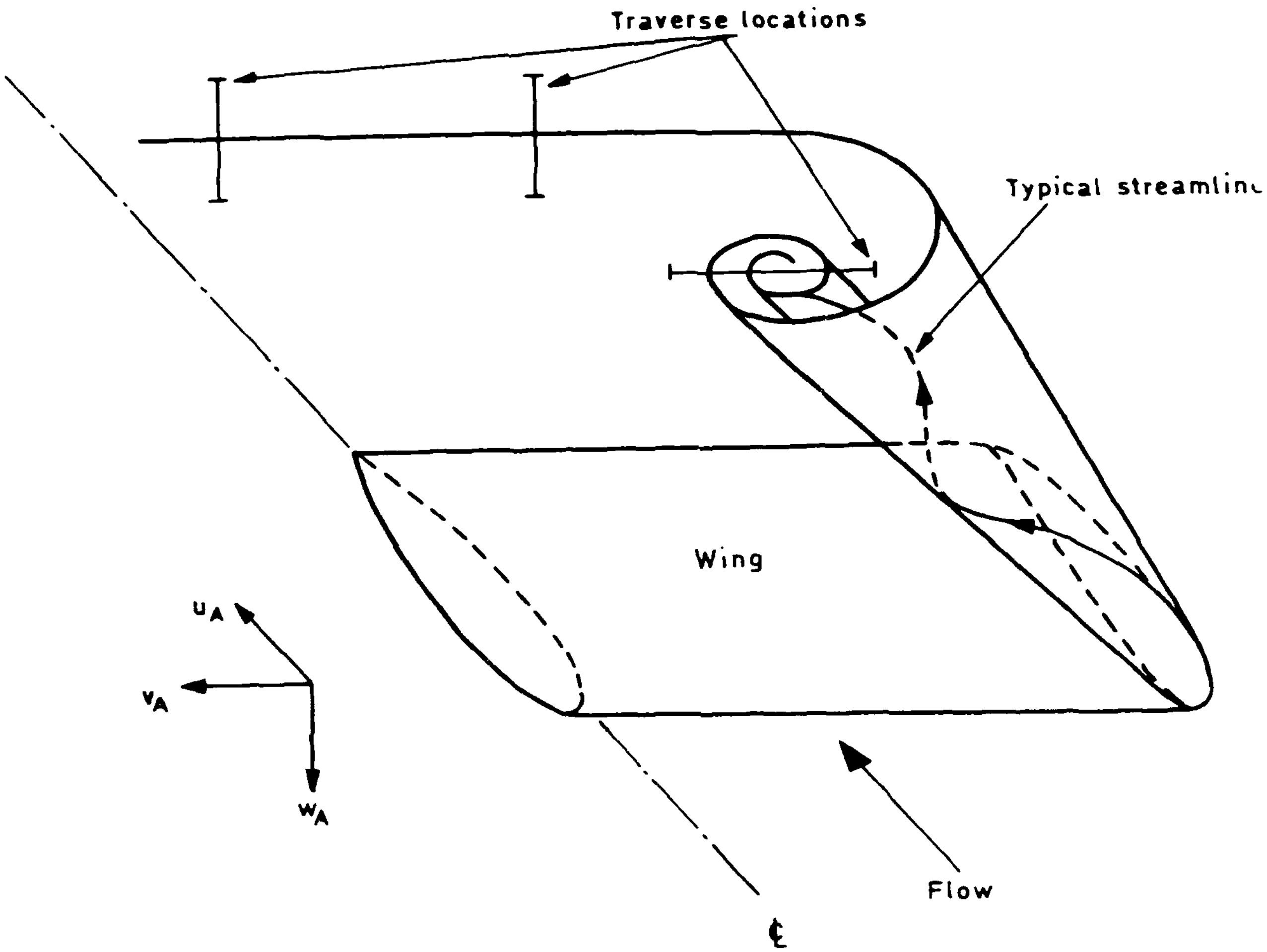

Fig 1 Structure of the flow

Fig 2

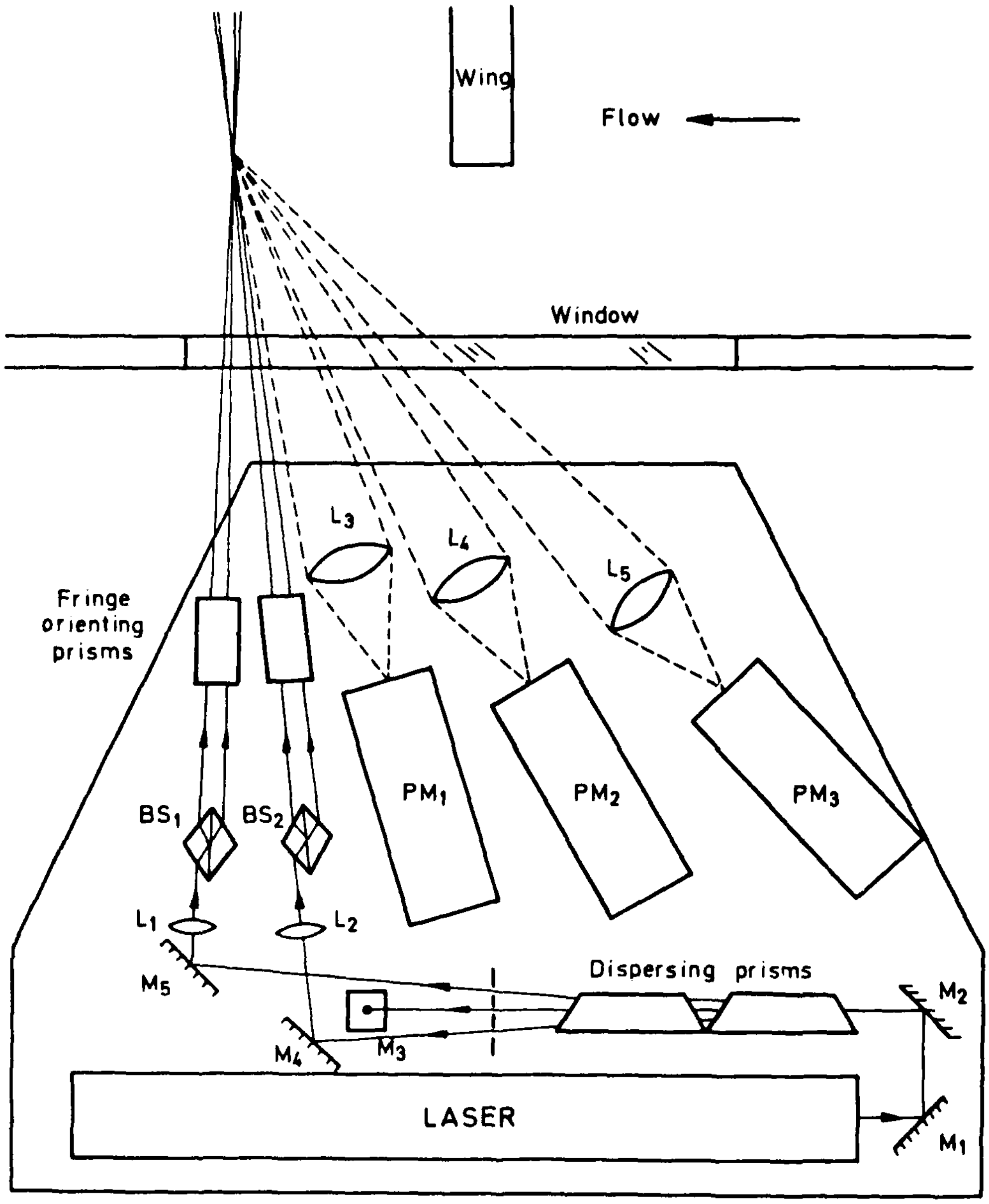

Fig 2 Optical arrangement

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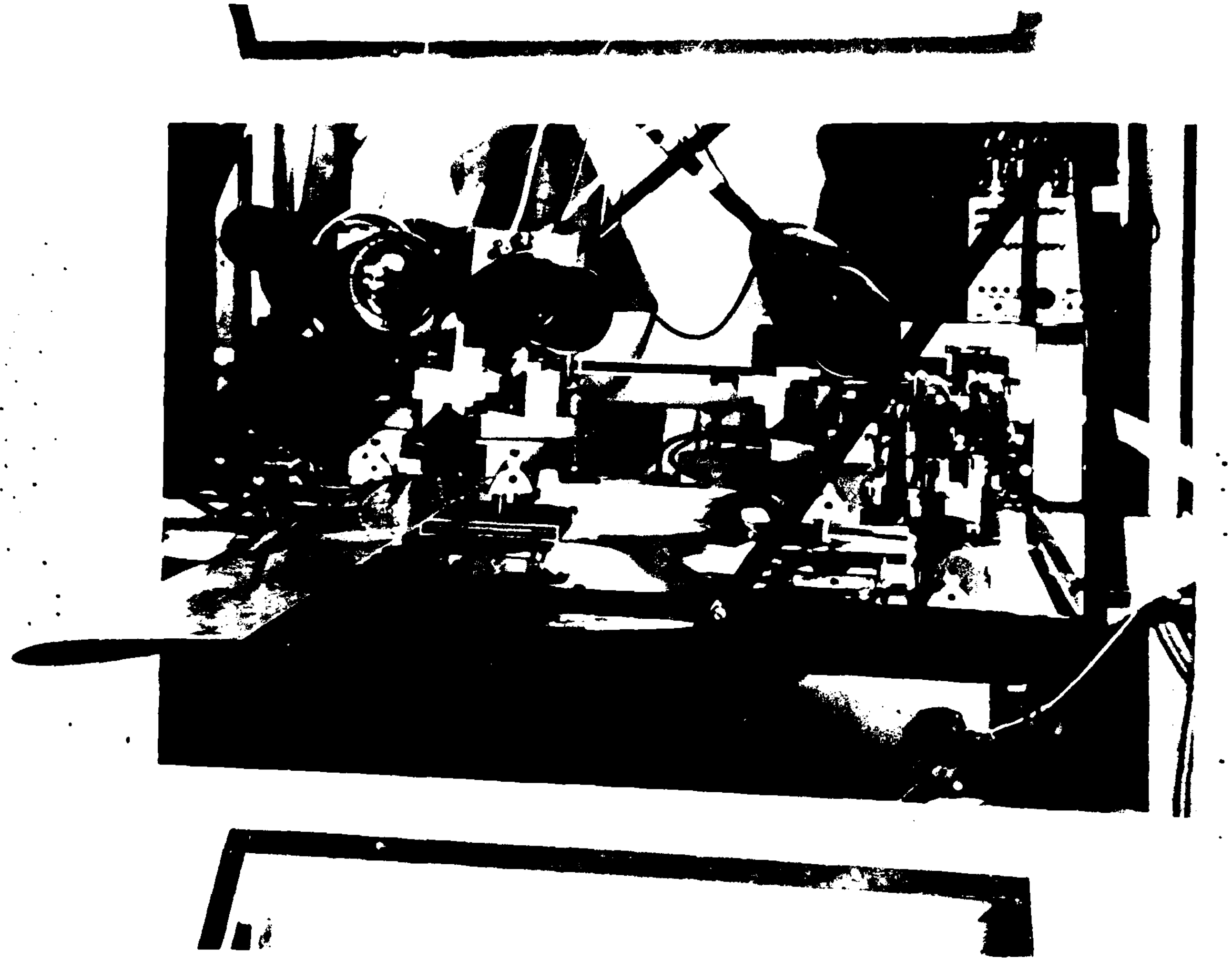

Fig 3 View from far side of test section, showing wing and collecting systems

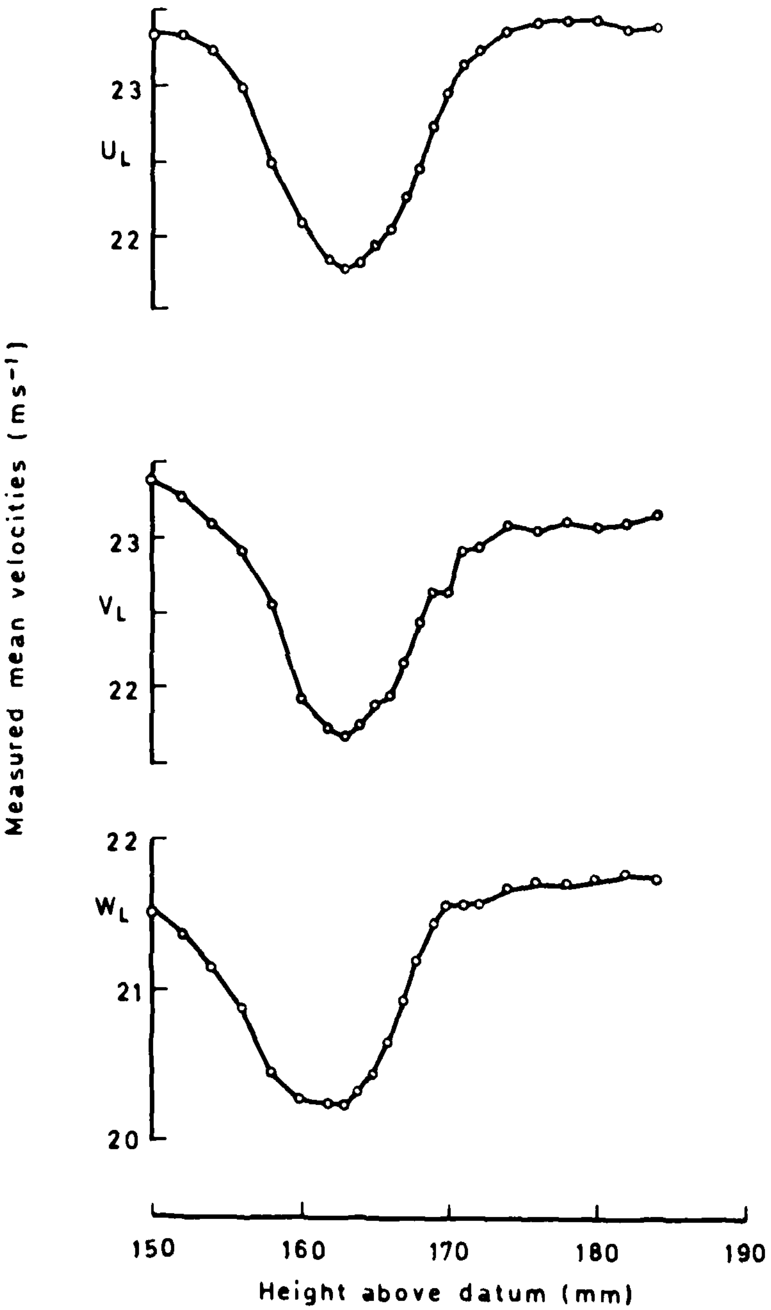

Fig 4 Vertical traverse through wake
(221 mm in from wing-tip, 3¾ chords downstream)

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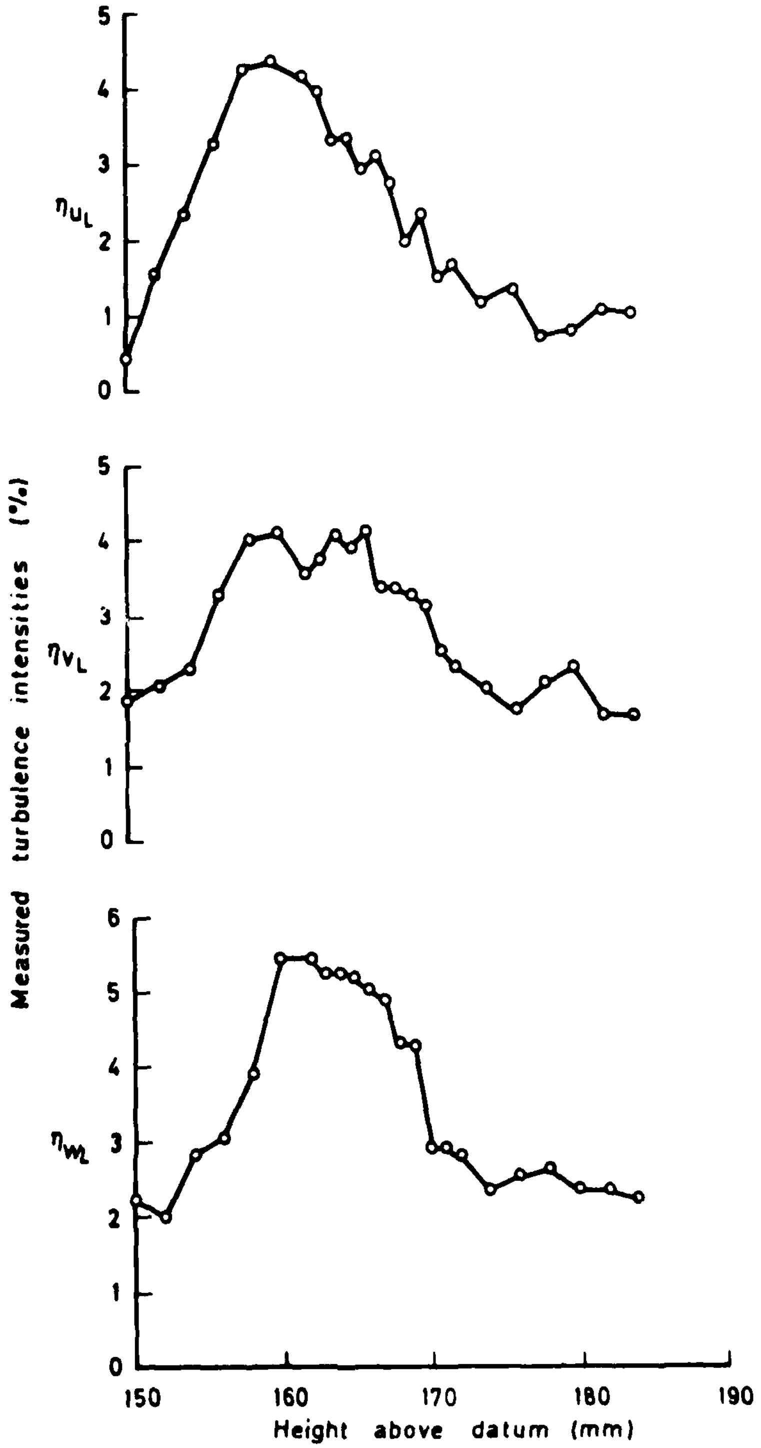

Fig 5 Vertical traverse through wake
(221 mm in from wing-tip, 3¾ chords downstream)

Fig 6

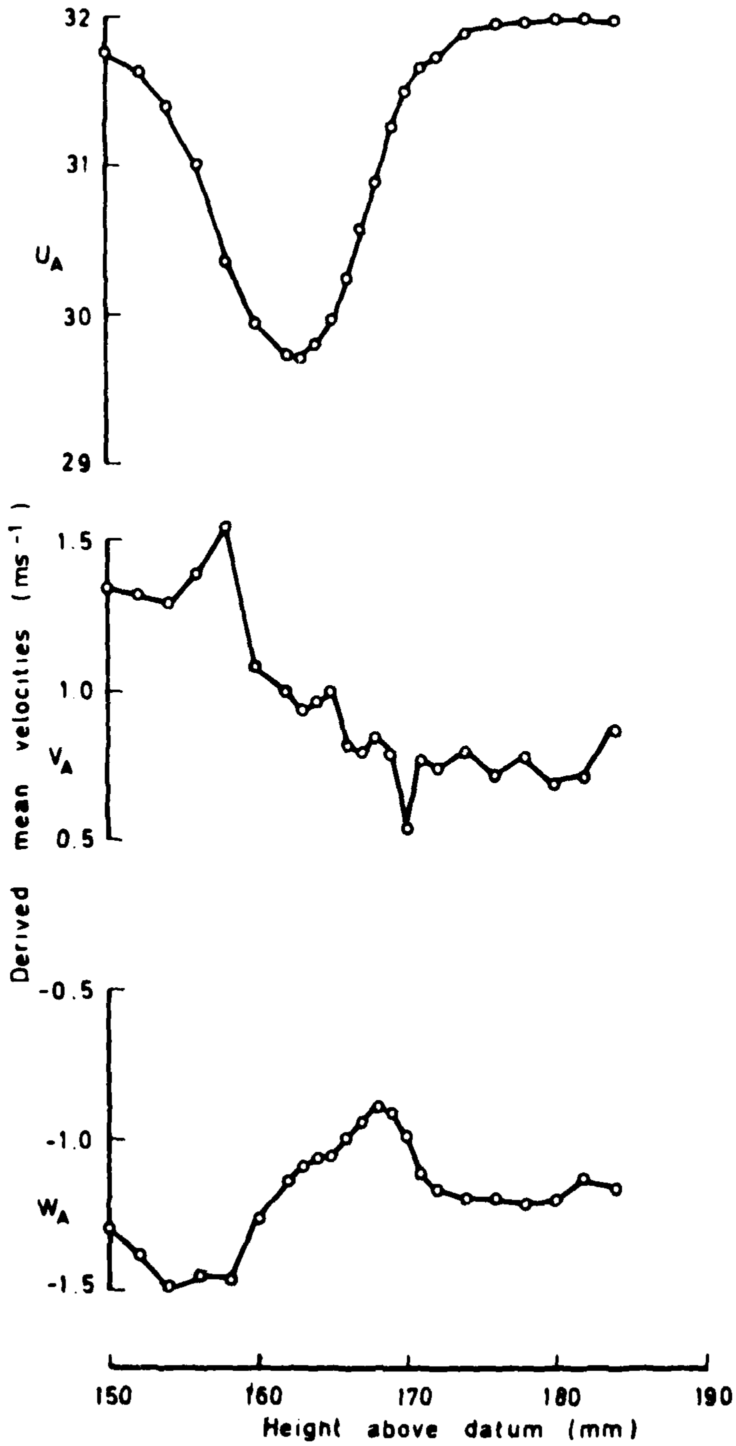

Fig 6 Vertical traverse through the wake
(221 mm from wing-tip, 3¾ chords downstream)

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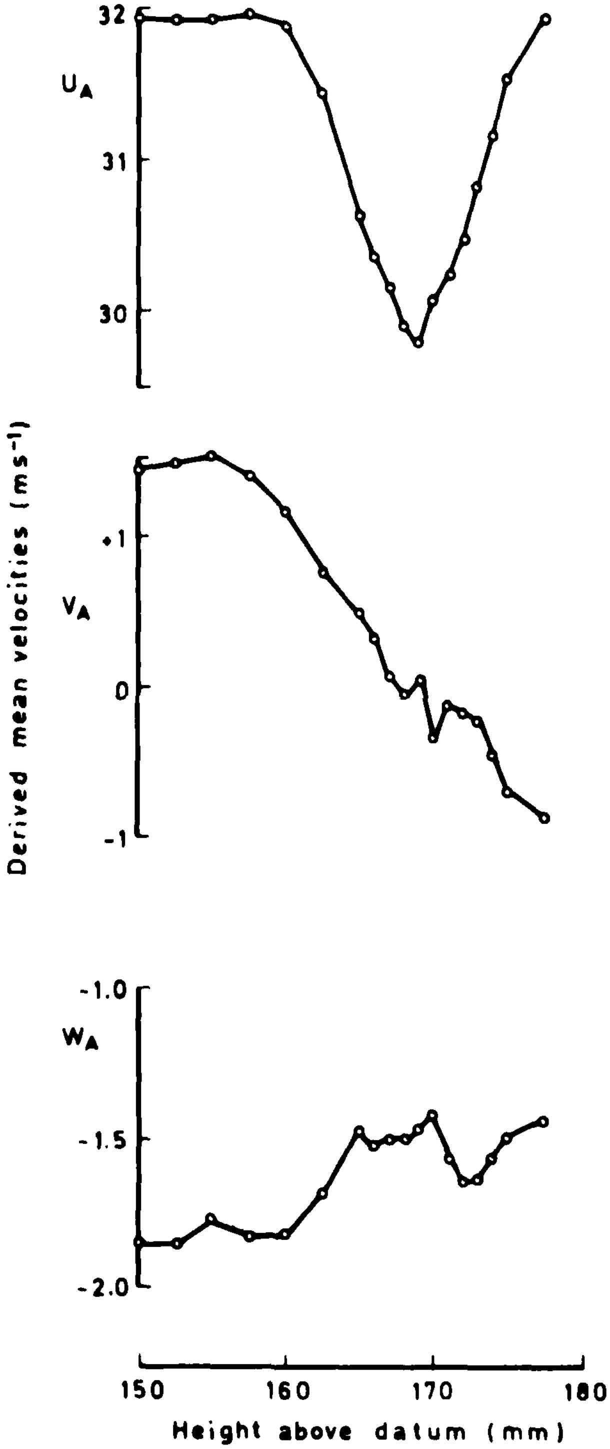

Fig 7 Vertical traverse through wake (71 mm in from wing-tip, 3¾ chords downstream)

Fig 8

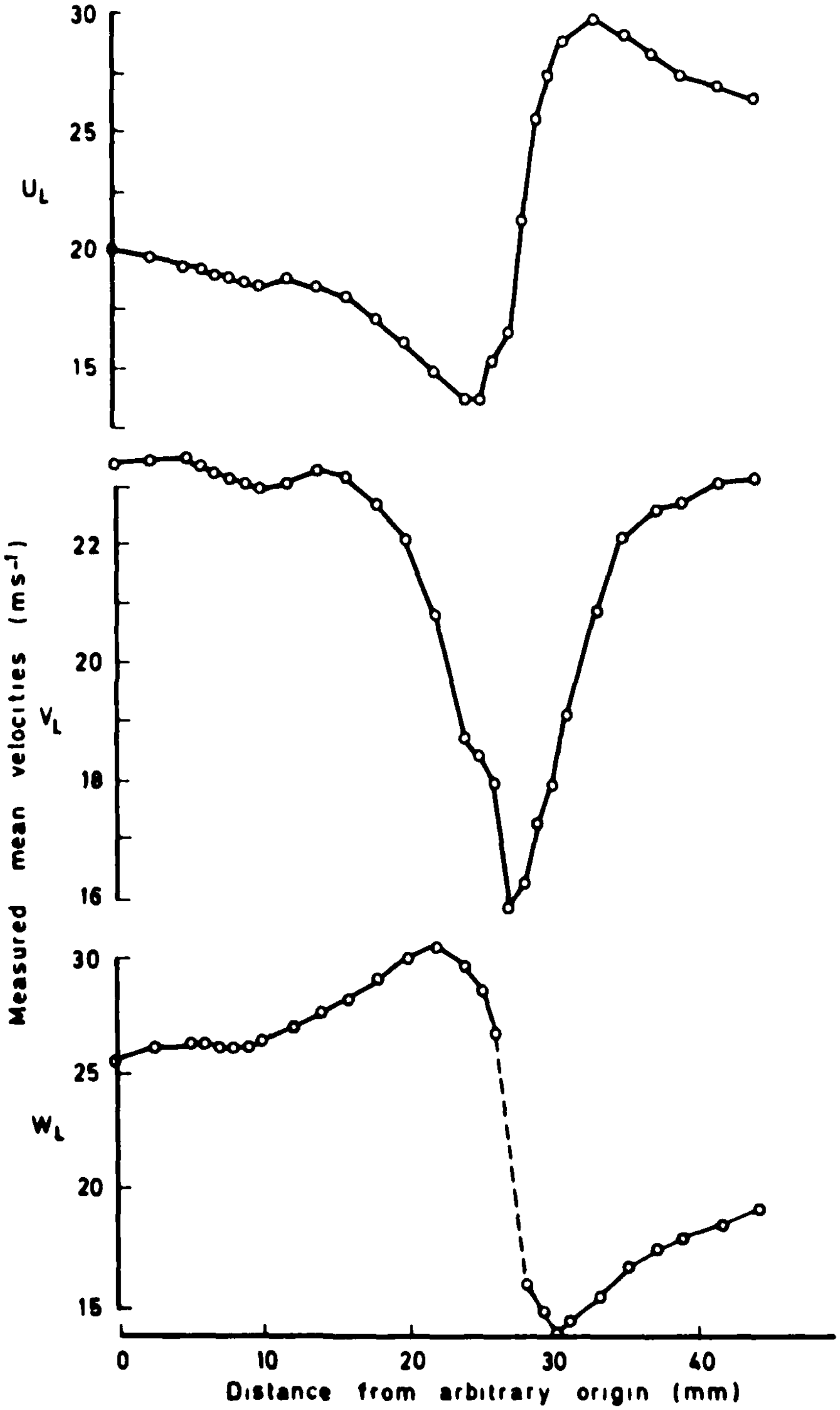

Fig 8 Horizontal traverse through vortex

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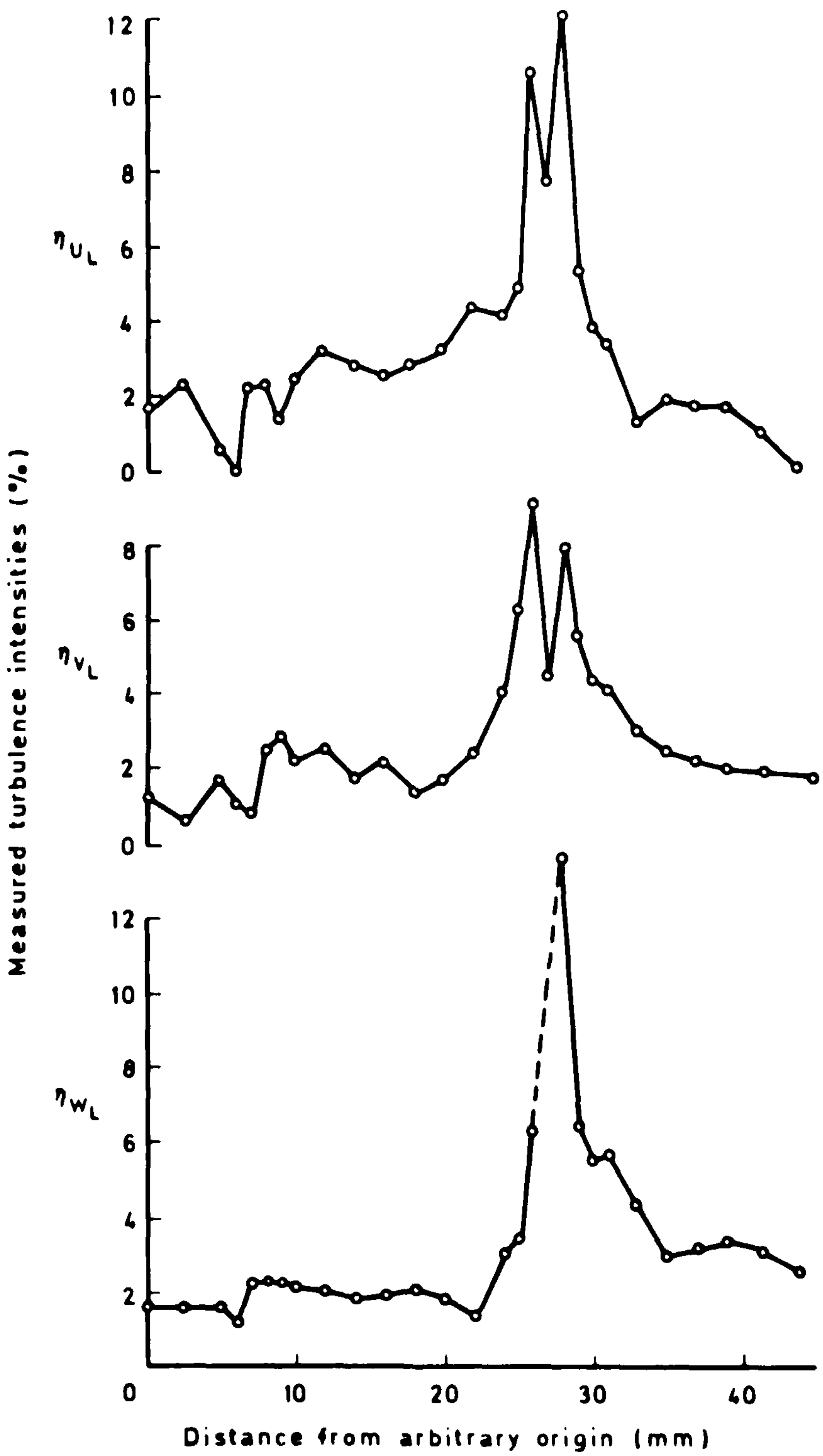

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Fig 9 Horizontal traverse through vortex

Fig 10

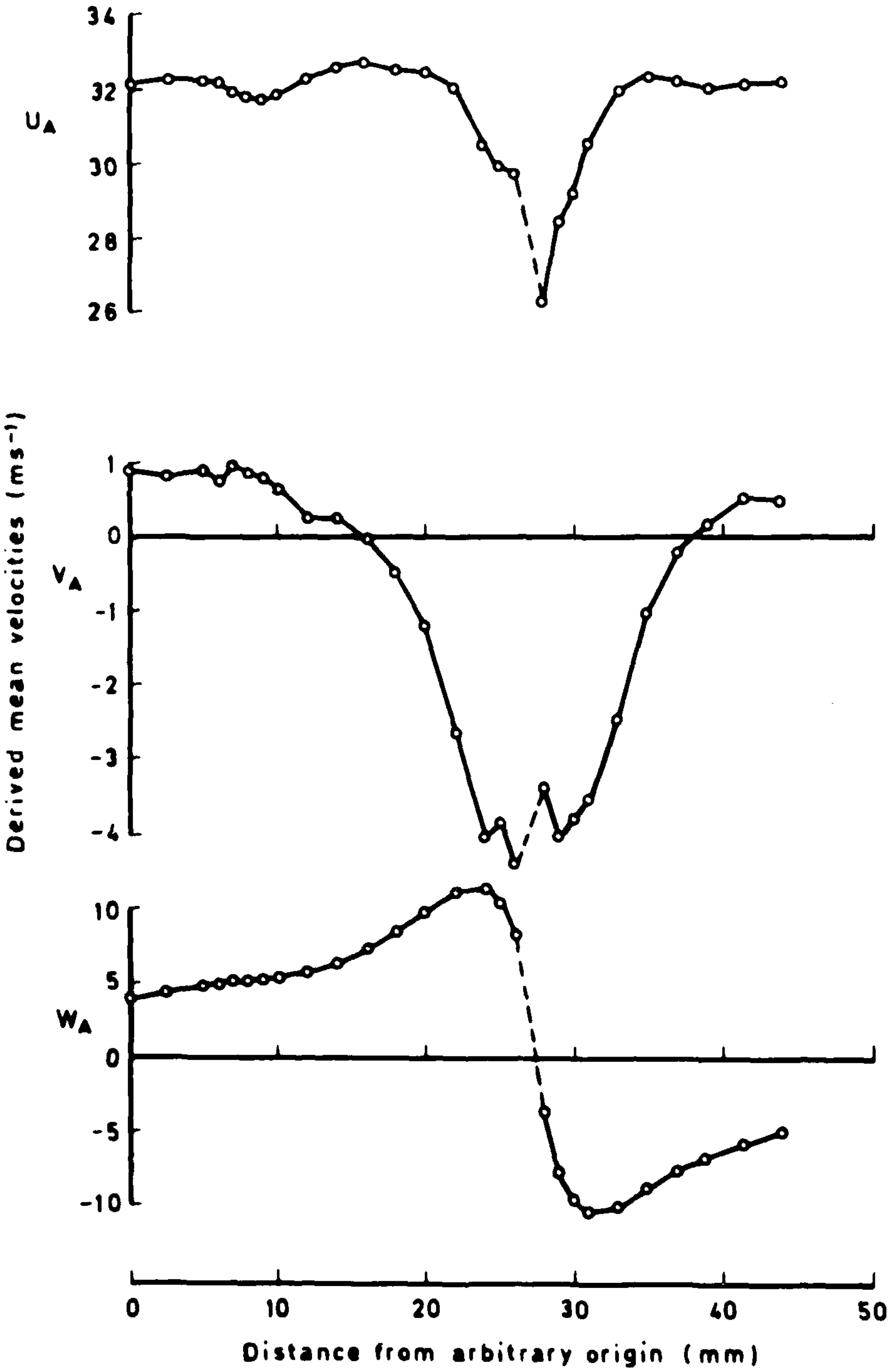

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Fig 10 Horizontal traverse through vortex

REPORT DOCUMENTATION PAGE

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17. Abstract

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